

Evaluation of COTS Electronic Parts for Extreme Temperature Use in NASA Missions

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Abstract - Electronic systems capable of extreme temperature operation are required for many future NASA space exploration missions where it is desirable to have smaller, lighter, and less expensive spacecraft and probes. Presently, spacecraft on-board electronics are maintained at about room temperature by use of thermal control systems. An Extreme Temperature Electronics Program at the NASA Glenn Research Center focuses on development of electronics suitable for space exploration missions. The effects of exposure to extreme temperatures and thermal cycling are being investigated for commercial-off-the-shelf components as well as for components specially developed for harsh environments. An overview of this program along with selected data is presented.

I. Needs for Extreme Temperature Electronics

Space exploration missions will require electronic parts and circuits that can operate reliably and efficiently in extreme temperature environments below or above typical device specification temperatures. While high temperatures are encountered in certain missions, others require exposure of electronics to cryogenic temperatures. In addition, there are circumstances where electronic systems on board spacecraft are subject to wide-temperature swings and thermal cycling. For example, an interplanetary probe launched to explore the rings of Saturn would experience an average temperature of about -183 °C near Saturn, and electronics deployed near Pluto, for instance, would be exposed to temperatures as low as -229 °C. In lunar applications, electronic systems experience temperatures of about -170 °C at the moon's equator, and about -235 °C in the shadowed polar craters. Also, systems designed for use behind the sun shield on the NASA James Webb Space Telescope will require the use of cryogenic detectors to capture weak distant signals. At the other end of the spectrum, high temperatures are anticipated in deep space missions such as probes and landers for planetary exploration of Venus (average surface temperature >485 °C) and Mercury. Presently, spacecraft operating in the harsh environment of space incorporate some kind of thermal management systems to maintain the temperature of the on-board electronics at approximately 20 °C. In cryogenic environments, for example, spacecraft carry on-board a large number of radioisotope heating units (RHUs) to provide and maintain a temperature for proper operation of electronics. This is not an ideal solution because the radioisotope heating units produce heat continuously, even when the spacecraft may already be too hot, thus requiring an active thermal control system for the spacecraft. In addition, RHUs add expense and require elaborate heat-spreading structures. For high temperature environments, cooling mechanisms are provided so that electronics can withstand the harsh surroundings and operate without failure due to thermal runaway or overheating.

The need for electronics capable of operation in extreme temperatures is not limited only to outer space ventures, but it also encompasses aerospace, military applications, and many terrestrial industries. Earth-orbiting satellites, for example, are expected to be subjected to repeated thermal cycling covering a wide temperature range. Jet engine distributed control architecture requires sensors and related circuitry to be co-located with actuators and transducers in the engine's hot zone where temperature can easily exceed +150 °C. While power-by-wire aircraft involve high temperatures, space-based infrared system satellites and astronomical observatories require operation of electronics at cryogenic temperatures. Similarly, extreme temperatures (both low and high) are encountered in terrestrial

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applications that comprise magnetic levitation transportation systems, power generation facilities, down-hole instrumentation for gas and oil exploration, automotive, medical imaging, particle acceleration and confinement, and Arctic and Antarctic exploratory missions.

II. Benefits of Extreme Temperature Electronics

Besides meeting the environment operational conditions, electronics that are able to tolerate and operate efficiently in extreme temperatures will negate the need for the traditional thermal control elements and their associated structures for proper ambient operation. This, in turn, will lead to many other benefits including decreased overall system mass and size, simplified design, and reduced power requirements. In addition, reduced development time and launch costs of space-based systems, as well as extended mission operations for longer exploration time can be achieved. Therefore, it is highly desirable and vital to have electronic systems capable of withstanding and operating reliably in hostile temperature environments without the need of heating or cooling. It should be pointed out that power electronic circuits designed for operation at low temperatures are expected to result in more efficient systems than those at room temperature. This improvement results from better behavior and tolerance in the electrical and thermal properties of semiconductor and dielectric materials at low temperatures¹. In particular, the performance of certain semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature (-196 °C). At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity.^{2,3} An example is the power MOSFET that has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance RDS(on) resulting from increased carrier mobility⁴.

III. NASA GRC Extreme Temperature Electronics Program

The majority of the commercial-off-the-shelf (COTS) components are rated for operation between 0 °C and 70 °C. These parts have limitations for use in extended temperature ranges due to the materials used, device design and packaging, and manufacturing processes. Military-grade devices are rated at -55 °C to +125 °C and use some different processes. Limited information is available on the performance of components and circuits outside these temperature ranges. In addition, little is known about the effect of thermal cycling that is typical of many space missions. These reliability data are needed by the mission system designers and are critical to the design process and to establishment of risk factors. To address these requirements and to provide enabling technologies that allow development and operation of electronic systems in harsh environments, an Extreme Temperature Electronics Program exists at the NASA Glenn Research Center (GRC) that focuses on development of electrical components, circuits, and systems suitable for applications in the aerospace environment and deep space exploration missions. COTS devices and components are characterized in terms of their performance at extreme temperatures to determine their suitability for use in specific applications and to establish safe operating areas to mitigate risks. When viable commercial devices fail to meet mission requirements, efforts are then undertaken to develop advanced components. The investigations are not limited only to component parametric evaluation, but they embrace issues such as device packaging and interconnects. A wide range of electronic parts and circuits are investigated, and they include semiconductor switching devices, resistors, magnetics, digital-to-analog and analog-to-digital converters, DC/DC converters, operational amplifiers, oscillators, and special-purpose circuits. Traditional, as well as newly-developed technologies are examined to establish a baseline on functionality and to determine suitability for use in extreme temperature environments. For example, silicon-germanium (SiGe) transistors have emerged lately and are being used extensively in low power, very high frequency communication systems. Besides high switching speed and low power consumption, these devices can also be tailored through band-gap engineering to attain particular characteristics, and thus render them good candidates for cryogenic operation. Electronic parts based on silicon-on-insulator (SOI) technology provide faster switching, consume less power, and offer better radiation-tolerance compared to their conventional counterparts. They also exhibit reduced leakage and, thus, they are often designed for high temperature operation. Finally, MEMS (Micro-Electro-Mechanical Systems) technology shows a great promise in meeting requirements for increasing packaging density, power reduction, and system-on-a-chip integration.

IV. R & D Activities

Some of the devices and circuits that were recently characterized include silicon-germanium diodes and heterojunction bipolar transistors, silicon-on-insulator operational amplifiers, and MEMS oscillators. Results of some of these investigations follow.

A. SiGe Diode

Semiconductor devices that are manufactured based on silicon-germanium technology show a great promise for operation at very low temperatures. The introduction of germanium to the silicon lattice alters the properties of the silicon-germanium structure through modification of the band-gap. The forward voltage-current characteristics of a SiGe power diode obtained at various test temperatures are shown in Fig. 1. It can be seen that the diode's forward voltage drop increased as test temperature was decreased. The magnitude of this forward voltage drop of this diode increased from about 0.6V to about 0.83V when test temperature was decreased from 20 °C to -195 °C. At high temperature, i.e. +85 °C, the diode exhibited a decrease in its forward voltage drop as its value decreased to about 0.48V. The variation in the forward voltage drop with temperature is primarily due to temperature-induced changes in the physical characteristics of the semiconductor P/N junctions, which is typical of all types of diodes.

B. SiGe Transistor

The collector current (I_C) versus collector-to-emitter (V_{CE}) voltage of a SiGe heterojunction bipolar transistor (HBT) at various base currents are shown at test temperatures of +20 °C, -195 °C, and +85 °C in Fig. 2a through 2c, respectively. The current gain of this transistor was found to undergo gradual increase with decrease in test temperature from ambient to cryogenic temperatures. For example, the gain of this HBT transistor increased by a factor of about 1.4 in magnitude when the test temperature approached -195 °C, as shown in Fig. 2b. On the other hand, no major changes were observed in the transistor's current gain when test temperature varied from room to +85 °C temperature.

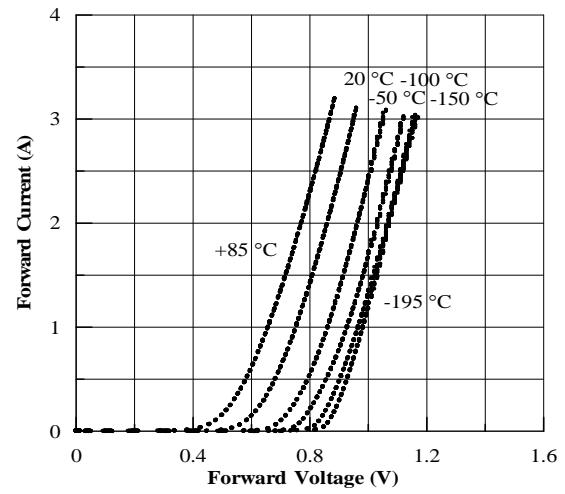


Figure 1. Voltage-current characteristics of a SiGe diode versus temperature.

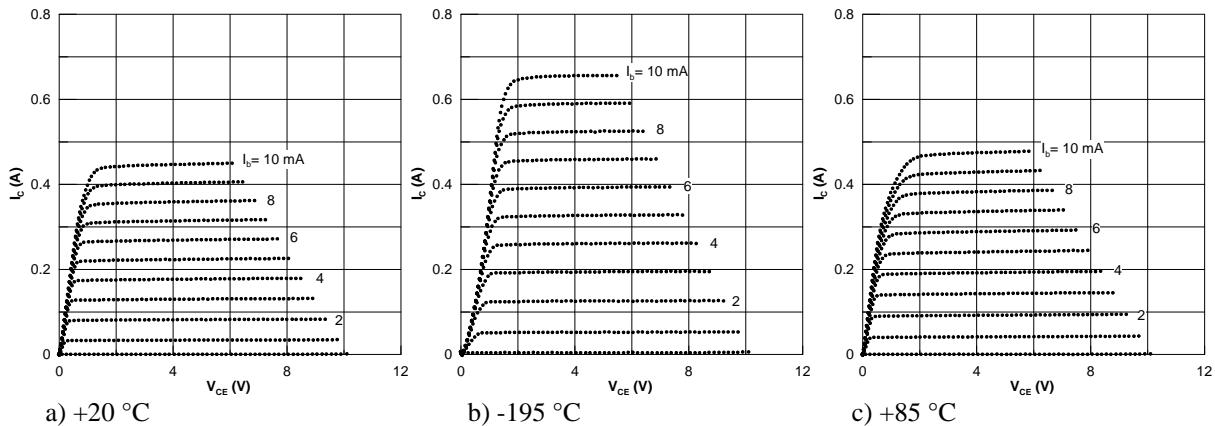


Figure 2. I_C versus V_{CE} of a SiGe HBT transistor at various temperatures.

C. SiGe Voltage-Controlled Oscillator

The oscillator output frequency of a silicon-germanium voltage-controlled oscillator at various tune voltages is shown in Fig. 3 over the test temperature range of +85 °C to -150 °C. For any given test temperature, the output frequency exhibited gradual increase (as expected) with increase in the external control tune voltage. It can be also seen that the frequency increased, almost linearly, as the temperature was decreased from +85 °C to -150 °C. This trend is observed at all levels of the applied tune voltage.

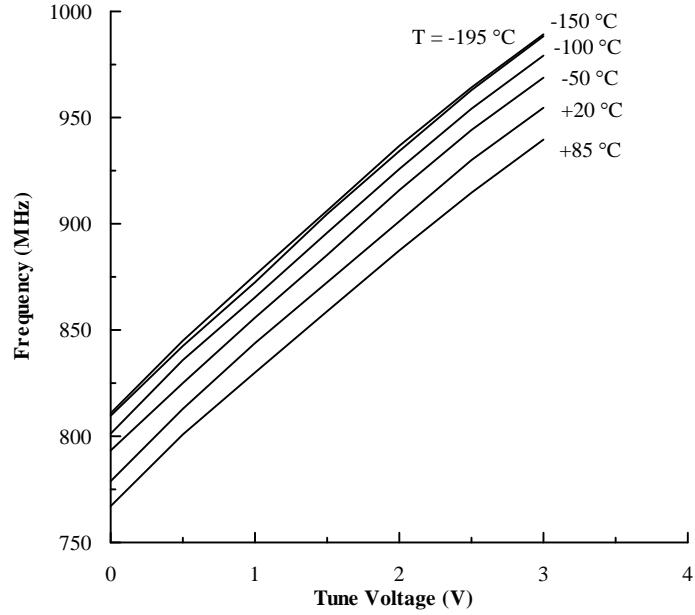


Figure 3. Oscillator frequency versus tune voltage at different temperatures.

D. MEMS Oscillator

Over the last few years, MEMS (Micro-Electro-Mechanical Systems) resonator-based oscillators began to be offered as commercial-off-the-shelf (COTS) parts by a few companies^{5,6}. These quartz-free, miniature silicon devices could easily compete with the traditional crystal oscillators in providing the timing for many electronic circuits. Figure 4 shows the output frequency of one of those MEMS oscillators as a function of temperature in the range of -110 °C to +100 °C. It can be clearly seen that this silicon MEMS oscillator exhibited excellent stability in its output frequency throughout the entire test temperature range. The duty cycle and the switching times characteristics of the output waveform were found not to have some variation with temperature between -110 °C and +100 °C. It should be pointed out that this particular chip is specified for operation between -40 and +85 °C.

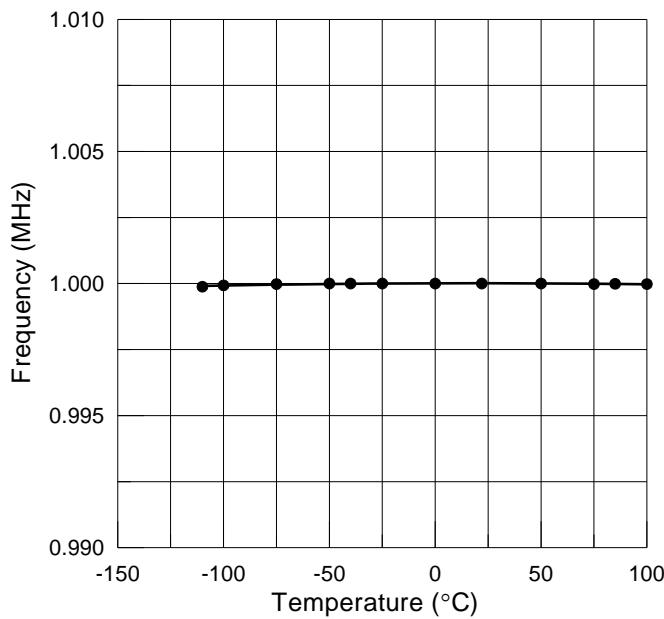


Figure 4. Output frequency of a MEMS oscillator versus temperature.

E. SOI Operational Amplifier

The gain of a silicon-on-insulator operational amplifier circuit at various test temperatures is shown in Fig. 5 over the frequency range of 1 kHz to 5 MHz. It can be seen that the gain of the amplifier remained relatively the same, regardless of the test temperature, until the test frequency of about 200 kHz was reached. Beyond that frequency, the gain exhibited changes in its magnitude and roll-off frequency. For example, while the roll-off frequency (-3 dB) was at 800 kHz at room temperature, it increased to about 1.1 MHz at the high temperatures between +100 °C and +200 °C. Conversely, when exposed to cryogenic temperatures, i.e. -100 °C to -190 °C, the roll-off frequency of the gain fell in the range between 400 and 500 kHz. Although the circuit was tested at ten different test temperatures between -190 °C and +200 °C, only data obtained for five temperatures are reported as the omitted data (0, -50, -150, +50, and +150 °C) followed the same trend depicted in Fig. 5. In terms of temperature, therefore, the amplifier circuit operated well in the temperature range between -190 °C and +200 °C; however, its bandwidth decreased slightly at low temperatures.

F. SiGe, SOI Operational Amplifier

A new prototype operational amplifier based on silicon-germanium and silicon-on-insulator technologies was recently introduced⁷. Since silicon-germanium electronics are good at cryogenic temperatures and their silicon-on-insulator counterparts are suited for high temperatures, such parts have the potential for use in areas where wide temperature swings are anticipated. Figure 6 shows the gain of such a device at various test temperatures in the frequency range of 1 kHz to 10 MHz. It is evident that the amplifier's gain maintained a flat plateau with test temperature, until the test frequency of 2 MHz was reached. Beyond that frequency, the gain exhibited changes in its magnitude and roll-off frequency. For example, while the roll-off frequency was at 6.5 MHz at room temperature, it increased to about 7 MHz at the high temperatures between +100 °C and +140 °C. Conversely, when exposed to cryogenic temperatures, i.e. -100 °C to -175 °C, the roll-off frequency of the gain fell in the range between 3 and 4 MHz. These changes are not significant, and the drop in gain at very high frequencies is typical of most operational amplifiers.

G. Temperature Sensor

A temperature-to-frequency relaxation oscillator circuit was assembled for potential use as a temperature sensor in the hot environment of jet engines. The circuit employed an SOI amplifier⁸, along with high temperature NPO multi-layer ceramic capacitors and power film resistors. A photograph of the circuit board is shown in Fig. 7. The circuit was evaluated at selected test temperatures between -195 °C and +200 °C in terms of its output frequency, variation in the output signal duty cycle and rise time, and the circuit supply current. Figure 8 shows the output

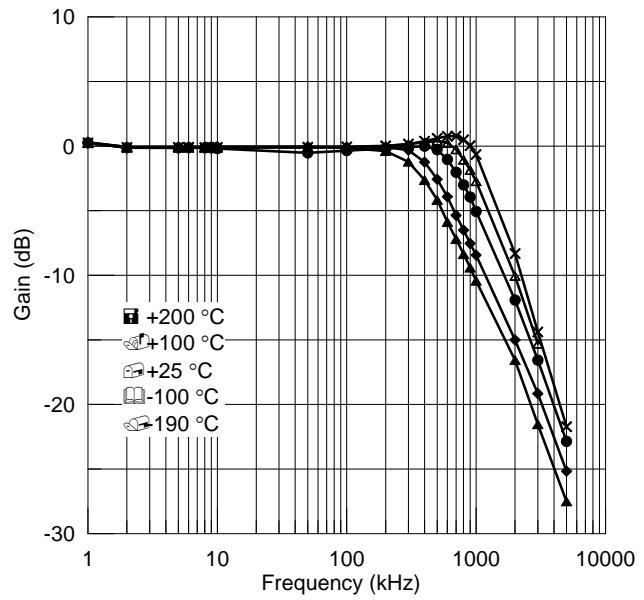


Figure 5. Gain versus frequency of a SOI amplifier at various temperatures.

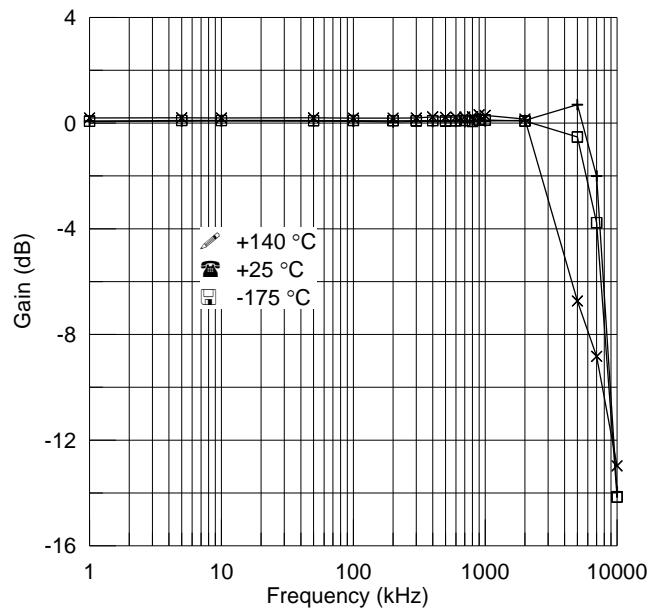


Figure 6. Gain versus frequency of a SiGe/SOI amplifier at various temperatures.

frequency of the sensor as function of temperature. It can be seen that the circuit performed very well throughout the temperature range between +200 °C and -195 °C, and as expected, the frequency of the output signal varied as a function of the sensed temperature, reaching a peak of about 9.2 kHz at test temperature of -195 °C and a minimum of 2.3 kHz at +200 °C. No change was observed by the duty cycle or the rise time of the output signal.

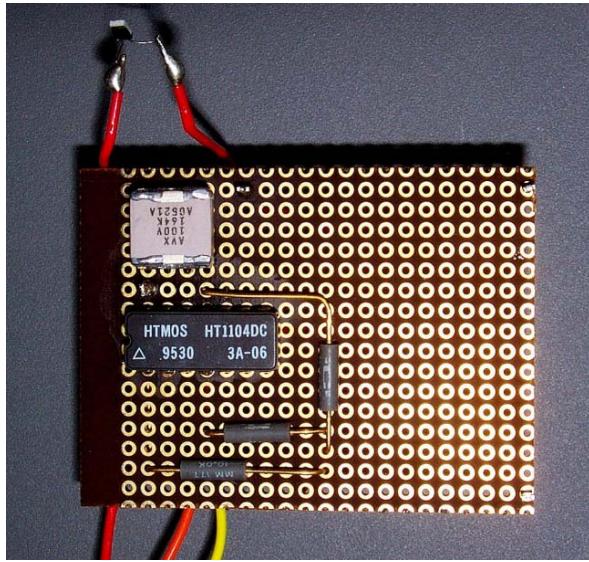


Figure 7. Temperature sensor circuit board.

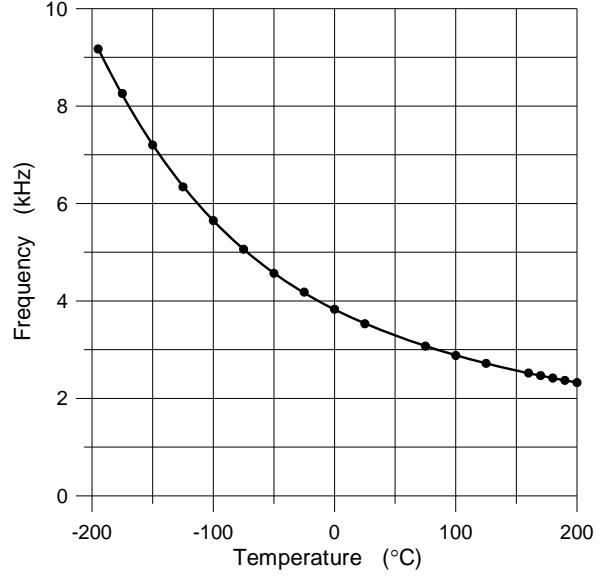


Figure 8. Output frequency of temperature sensor.

V. Conclusion

An overview of the Extreme Temperature Electronics Program at the NASA Glenn Research Center was given. NASA Glenn Research Center collaborates with other agencies, academia, and the aerospace industry to investigate electronic components and circuits for use in future space exploration missions. These efforts are focused on exploring selected, mission-driven, power and instrumentation components and systems and supporting technologies for extreme temperature operation. The on-going activities also include insulating material evaluation, power component characterization, and electronic system integration and demonstration. Other supporting research investigations comprise long-term reliability assessment of power devices and integrated circuits and the effects of extreme temperature exposure and thermal cycling on device interconnect and packaging. Preliminary and selected results were presented in this paper.

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